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A Crop Simulation Model for Predicting Yield and Fate of Nitrogen in Irrigated Potato Rotation Cropping System

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Simulation models are valuable tools to evaluate soil processes, crop growth, and production responses under varied agroclimatic and input-management production conditions. In this study, an upgraded potato (Solanum tuberosum L.) crop growth simulation model (CSPotato) was integrated with a multi-year, multi-crop simulation model (CropSystVB). The integrated CropSystVB-CSPotato model facilitated prediction of soil processes, and growth and yields of different crops in a potato rotation system under center pivot irrigation. The integrated model was validated using two years (2001-2002) of field data on 'Ranger Russet' cultivar grown in a Quincy fine sand in the Pacific Northwest Columbia Basin production region under different nitrogen-management practices. This study showed good agreement between the measured and predicted yields as well as N uptake across different N management practices in both years. The predicted water as well as nitrogen drainage below the potato rooting depth (0.6 m) was greater in 2002 than that in 2001. This study demonstrated that the upgraded potato model integrated with CropSystVB can be used as a valuable decision tool to predict the crop yields, fate, and transport of N in irrigated potato rotation cropping systems.

KEYWORDS *Natural resource management, decision support system, groundwater nitrate, nitrogen transformation, and nitrogen uptake*

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INTRODUCTION

Potato is an important crop in the U.S. Pacific Northwest (PNW) with total production in Idaho, Washington, and Oregon ranking 1st, 2nd, and 4th in the country, respectively. The production occurs mainly under irrigation systems, predominantly center pivots, and mostly on low organic matter sandy soils. Soils with low retention capacity for nutrients and water and shallow-rooted crops increase the potential for N leaching. Excess irrigation, combined with a high N rate as in some cases, has contributed to leaching of nitrate_nitrogen (NO_3^-N) below the shallow root zone of potatoes. The above trend would raise concerns with respect to negative impacts on groundwater quality, i.e., non-point source pollution of groundwater by NO_3^-. Improved N management practices, combined with careful irrigation scheduling, are necessary to increase crop nutrient-uptake efficiency and minimize N losses to groundwater.

Sustainable agricultural production practices aim toward: (i) optimal utilization of inputs; (ii) maximizing crop production and crop quality as well as net returns; and, (iii) minimum negative effects on the environment. The optimal combination of various inputs to attain the above objectives can be arrived at by experimentation and measurement of crop-production responses and the effects on the environment. Such experiments cannot be repeated under a wide range of production conditions. Thus, simulation models provide valuable tools to analyze the behavior of agricultural systems under a range of climatic and geographical production conditions (Peralta & Stockle 2001). A good decision model should be capable of predicting the soil processes as well as plant growth, biomass accumulation, and production. An example of soil processes and crop-response simulation model is integration of Expert-N (a model for simulation of daily fluxes of water, carbon, and nitrogen; Engel & Priesack, 1993; Priesack, Sinowski, & Stenger 1999; Stenger et al. 1999) with Soil Plant Atmosphere System Simulation (SPASS), a process-oriented model for simulation of crop growth and uptake processes. Gayler and colleagues (2002) modified the SPASS model for potatoes. They used LEACHN (Leaching and Chemistry for Nitrogen; Hutson & Wagenet 1991) for prediction of soil processes. They demonstrated that the modified SPASS model adequately described the N uptake and plant growth under different N fertilizer applications.

Hodges, Johnson, and Johnson (1992) developed SimPotato model to simulate soil processes and potato plant growth. Han and colleagues (1995) interfaced SimPotato with a GIS (geographic information system) software (Environmental Systems Research Institute 1992) to study potato yield and N leaching distributions. They showed that areas of high N leaching corresponded to areas with high water and N applications. Thus, Han and colleagues (1995) recommended improving sprinkler irrigation uniformity to reduce N leaching and increase potato yields.

Timlin (Dennis Timlin, unpublished data) incorporated a robust, two-dimensional soil and root processes model (2DSOIL; Timlin & Pachepsky 1997) into the SimPotato model. This integrated model called 2DSPUD was evaluated to predict potato yield and N leaching under different N fertilizer management and irrigation regimes (Jed Waddell, personal communication). They reported a close relation between the simulated vs. measured potato yields, N uptake, and N leaching.

Gayler and colleagues (2002) validated another model, SPASS, to simulate the growth, tuber yields, and N uptake of early and late potato varieties in Europe. Their study showed that the above model predicted tuber yields and N uptake quite well in comparison with the actual measured responses for both early and late potato varieties.

The overall long-term objective of this study was to develop computer-based tools that can be incorporated into a decision support system to optimize productivity of the potato-based agricultural systems while minimizing negative effects on the environment. The specific objective of this study was to describe a potato simulation model and illustrate its application to predict the fate and transport of N below the root zone of potato under different levels of N and water-management practices.

MATERIALS AND METHODS

The Model

The model used in this study was CropSystVB- CSPotato, an integration of the multi-year, multi-crop simulation model CropSystVB with the potato crop simulation model Simpotato (Hodges, Johnson, & Johnson 1992), which was modified and upgraded into CSPotato model (Javier Marcos, unpublished data). CropSystVB is a Visual Basic new version of the CropSyst model (Stockle, Martin, & Campbell 1994; Stockle, Donatelli, & Nelson 2003). CropSyst has been widely used to evaluate crop production and management strategies worldwide, specifically in the U.S. Pacific Northwest (Stockle, Donatelli, & Nelson 2003). In the integrated model, CropSystVB provides the framework for weather, location, soil, and crop inputs and for daily and annual soil and crop outputs. CropSystVB includes a mechanistic approach of the soil-water-plant-atmosphere system. It simulates crop growth and development, and soil water and N balances for a crop rotation across several years. SimPotato is based on the CERES-maize type of model and simulates growth and development of potato. In CropsystVB-CSPotato, when the crop in the rotation is potato, the phenology and growth of potato, as well as the plant N and carbon (C) balances, are simulated by CSPotato model.

Because the original SimPotato model has been modified, a brief description of the growth and phenology submodels in the modified CSPotato version is presented below. Details of these modifications/updates are presented elsewhere. Detailed description of CropSyst is published by Stockle, Martin, and Campbell (1994), and Stockle, Donatelli, & Nelson (2003).

Simulation of Development

In SimPotato, determination of pre-emergence stages, i.e., sprout germination and emergence, is based on the management and soil thermal time. Germination of potato seeds occurs immediately after planting if seeds are planted with sprouts already present. Otherwise, germination and sprout growth depend on soil thermal time. Emergence occurs when the sprout length is greater than the planting depth. However, emergence date can also be treated as an input because of the variability and uncertainty of the effects of harvest and storage conditions on the rate of germination and sprouting. Seed reserves are used to support sprout and root growth during this stage.

Development during the post-emergence growing stages is simulated based on the induction that the plant receives from the environment to form tubers (tuber induction, TIND). Flowering is not simulated in SimPotato. Phenological post-emergence events are tuber initiation (TI), beginning of rapid tuber growth, or bulking and maturity. Tuber induction is estimated using the approach in Substor potato crop model (Griffin, Johnson, & Ritchie 1993). In the Substor model, TIND is a function of cultivar response to both temperature and photoperiod, and these responses are modified by soil water and plant N status. The temperature and photoperiod effects on TIND are simulated by dimensionless cultivar-specific factors that range from 0 to 1. A daily tuber-induction index is accumulated across the growing season and TI and the start of bulking occur when TIND reaches predetermined threshold values.

From TI to the beginning of bulking, carbon partitioning occurs between tops, roots, and tubers. Bulking is the stage of dominant tuber growth. Tuber growth frequently ends (maturity) when all leaves senesce due to various stresses or as a result of defoliation in preparation for harvest.

Carbon Assimilation, Partitioning, and Nitrogen Balance

Growth (g carbohydrate/plant) in CropSystVB- CSPotato model is the minimum of potential growth that can be supported by the available carbohydrate. Potential growth is the sum of potential growth of leaves, stems, tubers, and roots. Temperature is the main environmental factor that determines potential growth. Available C is the sum of potential C assimilation (carbo) and seed reserves. Potential C assimilation is computed as the minimum of light and water limited growth and is supplied by CropSyst.

From emergence to TI, only leaf, stem, and root growth occurs. After TI, tuber growth is also calculated. By performing a C balance, potential growth is compared with available C. This balance attempts to match available C to potential growth. If available C is greater than potential growth, the excess C is discarded. Otherwise, if available C is less than potential growth, growth is reduced. During tuber-bearing stages and for determinant varieties, tuber growth is given first priority according to a crop parameter that sets the level of tuber priority for carbon allocation. The resulting growth is the amount of growth that will occur unless N is limiting.

Potential leaf growth is estimated from potential leaf area expansion using a cultivar-specific coefficient for specific leaf weight (g/cm^2). Potential leaf-area expansion is obtained from daily thermal time, a cultivar-specific maximum leaf expansion rate (cm^2/plant/day), and water and N stresses. Potential stem growth is initially estimated to be 1/3 of potential leaf growth and then adjusted during the C and N balances. Potential maximum tuber growth is calculated as the product of the cultivar-specific maximum for tuber-growth rate (g dry weight/plant/day) and the fraction of available C apportioned to tubers. This fraction depends on TIND and temperature. Nitrogen shortage reduces top growth and increases tuber growth. Available soil N is estimated by CropSyst and supplied to CSPotato model. Leaf senescence caused by normal aging is based on thermal time and existing leaf area. Senescence caused by stress is estimated as the minimum of water, N, temperature, and excessive leaf-area stress factors.

Plant nitrogen demand (Ndem) is the N needed for optimum N concentration of existing biomass and new growth. If available N (availN) is greater than Ndem, leaf N concentration is set to the maximum allowable concentration. If availN is less than Ndem, leaf N surplus (if any) above a specified threshold will be available for redistribution. If N shortage persists, Ndem is based on new growth only. If availN is still not enough to match Ndem, growth is reduced until availN equals Ndem. During the tuber-bearing stages, if demand and supply are not in balance, there is a shift of growth from leaves to stems and tubers according to the available N:C ratio.

A Simulation Example

An example is presented to illustrate model capabilities for assessment of N dynamics in potato-based agricultural systems in the U.S. Pacific Northwest. Crop, soil, weather, and management inputs are subsets of the data from long-term potato N management experiments conducted by A.K. Alva (2001-2003; unpublished data). A corn-potato-wheat rotation was simulated from 2001 to 2003 in a sandy soil in the Columbia Basin region in Washington. The data used for this simulation are for two pre-plant N application rates (0 and 112 kg/ha) for 'Ranger Russet' cultivar. The simulation was done at standard irrigation, i.e., replenish 100% evapotranspiration (ET), and at excess irrigation, i.e., irrigation to replenish 130% of daily ET. The total N applied (including the residual soil N) for the entire potato-growing season was 336 kg/ha for both pre-plant N rate treatments. The in-season N rates were delivered in five applications. Total N applied to corn and wheat was 250 and 130 kg/ha, respectively, and the irrigation for these two crops was equivalent to potential crop ET.

Field Experiment

'Ranger Russet' cultivar was grown for two years (2001 and 2002) in a Quincy fine sand (mixed, mesic Xeric Torripsamments) in the Columbia Basin region in Benton County, Washington. Different rates of pre plant N rates (including the residual soil) were: 0, 56, and 112 kg/ha in 2001 (soil residual N at planting was 56 kg/ha), or 56, 112, and 168 kg/ha in 2002 (with negligible soil residual N at planting). The total N for the entire growing period across all treatments was 336 kg/ha, including the soil residual N. An additional treatment of 448 kg/ha total N with 112 kg/ha pre-plant N was also evaluated. The in-season N was applied (at weekly interval, four weeks after seedling emergence) at 5 and 10 frequencies in 2001 and 2002, respectively. Center pivot irrigation was used to supply water to replenish the crop ET on a daily basis. Tuber yields were measured for all treatments. Plant N uptake was estimated based on the plant sampling to measure the dry matter and N concentration. Total as well as marketable tuber-yield response and N uptake and partitioning under different N management practices are reported elsewhere (Alva 2004).

RESULTS AND DISCUSSION

Simulated N transport below 2 m depth of soil during the growing seasons of potato and wheat and during the winter period following potato are shown in Table 1. Results showed that irrigation level was the most important factor contributing to fate of N. Transport of N below 2 m was almost negligible when the applied water was just enough to replenish the deficit in crop potential ET. Comparing pre-plant N rates with irrigation at 130% of potential crop ET, N transport below 2 m during the potato growing season and during

TABLE 1 Simulated N Leaching (kg/ha) below the 2 m Depth for the 0 (PP0) and 112 (PP112) kg/ha of Pre-plant N Treatments and Irrigation Regimes to Replenish 100% (100% ET) and 130% (130% ET) of Potential Crop ET

Season	PP0-100%ET	PP0-130%ET	PP112-100%ET	PP112-130%ET
		N leaching (kg/ha)		
Potato growing season	0	19.5	0	30.1
Winter after potato	0.1	26.1	0.1	30.7
Wheat growing season	1	13.8	1	10.8

the winter period following potato was greater for the pre-plant N rate of 112 kg/ha than that for the 0 N rate. High soil N at the beginning of the growing season in the 112 kg/ha pre-plant rate and excess irrigation water increased the amount of N transport below 2 m during and after the growing season of potato.

Table 2 contains potato and wheat N uptake and fresh-tuber yields. Simulated tuber yield decreased with increased irrigation levels at both pre-plant N rates. Increased N transport below the root zone affected the available N for crop uptake, particularly during the first part of the growing season. Low potato yields correspond to low N uptake. Nitrogen in the soil profile (2 m depth) at harvest of potato for the 130% ET treatment was distinctly greater than for the 100% ET (Figure 1). A large portion of this soil N was, however, below the root zone of potato (0.6 m), thus was not available for uptake by potato crop (Table 2). Nitrogen uptake by wheat was not significantly different among treatments despite the different amounts of N in the profile at the beginning of the growing season. Much of the N left by potato in the soil profile was located in the deep layers, and therefore wheat could not use most of it, at least at the beginning of its growing season.

Results illustrated how the CropSystVB- CSPotato model can be used to assess N transport and losses under different water and N management practices. The CSPotato component is based on the balance of plant available C

TABLE 2 Simulated N Uptake (kg/ha) by Potato and Wheat and Tuber Fresh Yield

	PP0-100%ET	PP0-130%ET	PP112-100%ET	PP112-130%ET
Potato N uptake (kg/ha)	248	165	241	186
Wheat N uptake (kg/ha)	159	162	149	147
Tuber fresh yield (Mg/ha)	89	66	83	73

(PPO) pre-plant N zero; (PP112) 112 kg/ha pre-plant N application; and (ET) crop evapotranspiration.

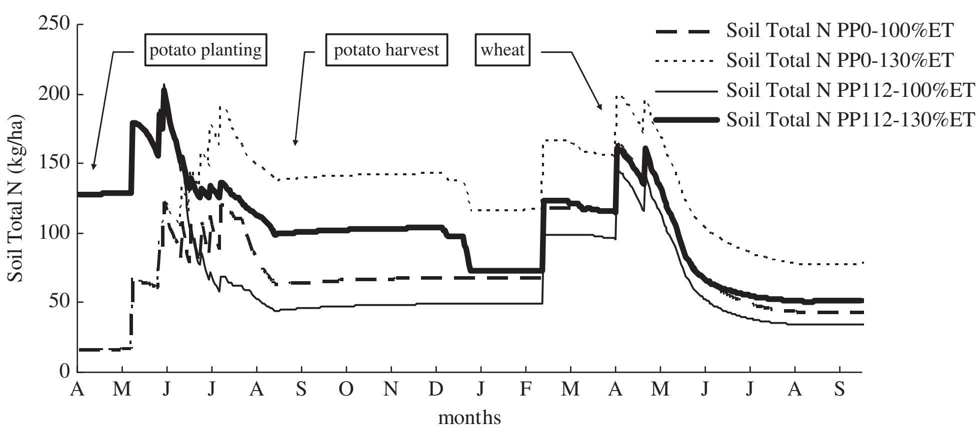

FIGURE 1 Simulated total soil N (kg/ha) during the growing seasons of potato and wheat.

and N. The integration of CSPotato into CropSyst gave the integrated model improved capabilities to estimate soil and plant N dynamics and production of potato-based cropping systems.

Example simulations showed that the irrigation level above potential crop evapotranspiration in potato appears to be a main factor influencing N transport in the predominantly irrigated Pacific Northwest production region in the USA. Timing of fertilization influenced the N transport in the soil profile. High rate of pre-plant N application increased the transport of N deeper in the soil, thus making it unavailable for crop uptake.

The model predicted the yield and N uptake reasonably well (Table 3, Figure 2). However, it tended to overestimate yields during 2002, particularly

TABLE 3 A Comparison of Measured vs. Predicted Tuber Yields and N Uptake, as Well as N Balance Predictions Including Potential N Leaching Losses

Evaluation parameters	2001				2002			
Pre Plant N applied (kg/ha)	0	56	112	56	56	112	168	112
Total N (kg/ha)	336	336	336	448	336	336	336	448
Measured Yield (Mg/ha)	64.5	78.6	64.1	78.9	65.8	67.2	68.4	61.6
Measured N Uptake (kg/ha)	186	242	210	274	189	207	225	214
Model predictions:								
• Predicted Yield (Mg/ha)	63.3	70.1	76.8	69.8	73.7	79.2	78.0	81.2
• Drainage (mm) (below 0.6m soil)	136	136	136	136	297	297	297	297
Nitrogen balance (kg/ha):								
• N in the root depth at planting	54	110	166	110	61	117	173	117
• N in the profile at harvest	102	82	73	159	38	30	25	56
• N uptake	221	235	240	270	212	224	214	263

Residual soil N at planting was 56 kg/ha in 2001, and negligible in 2002.

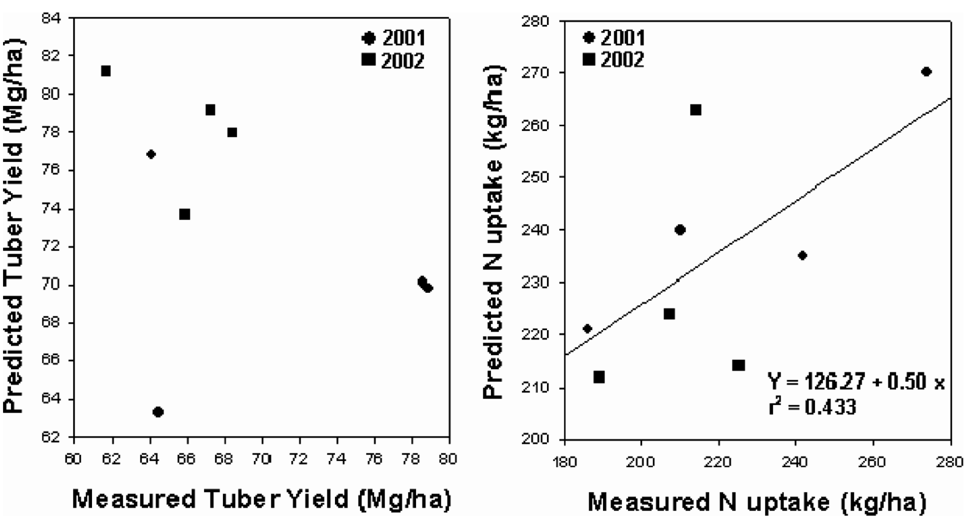

FIGURE 2 Comparison of predicted vs. measured tuber yields and N uptake.

for the highest N rate. The model simulated less N stress and greater leaf-area index and transpiration during the 2002 than the 2001 season. This might explain the simulated yields greater than that measured in 2002. Model simulations showed no significant yield increase with the highest N rate. Simulations also showed that, for the highest N rate, N unaccounted for in the rooting zone at the end of crop growth increased significantly, particularly during the year 2002. Irrigation applied in 2002 was about 215 mm greater than that in 2001. This excess of water increased drainage and, therefore, may have contributed to N loss from the soil. N uptake increased rapidly during the 60 to 100 days after planting (Figure 3), which coincided with the period of rapid dry matter increase (Figure 4). N uptake increased marginally at 448 than at 336 kg/ha total N treatment (Figure 4).

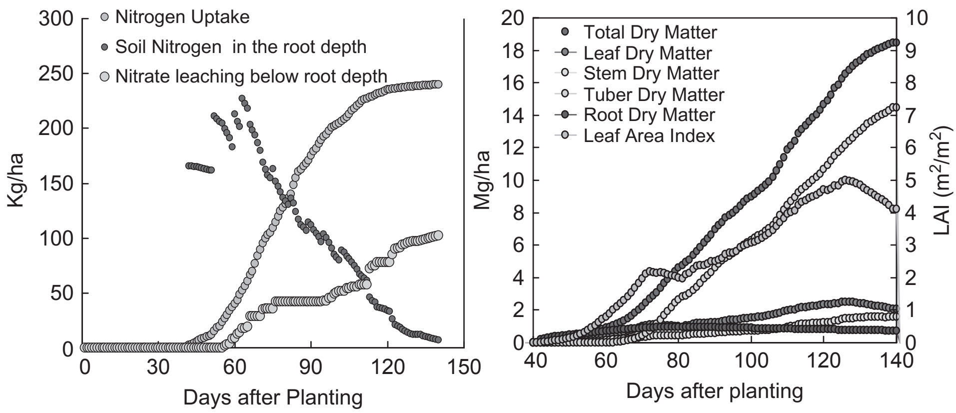

FIGURE 3 Predicted nitrogen uptake, soil nitrogen in the root depth, and nitrate leaching below the root depth (A: 2001 data for 112 kg/ha pre-plant N treatment), and predicted dry matter and leaf area index (B: 2001 data for 112 kg/ha pre-plant N treatment).

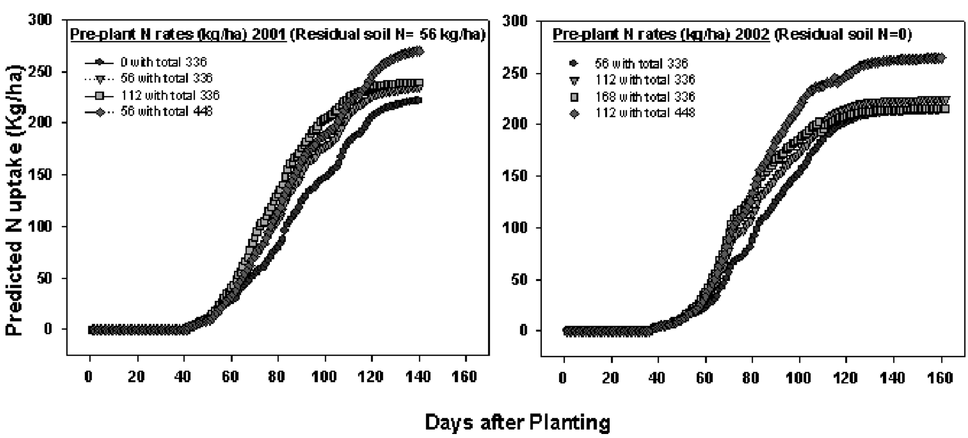

FIGURE 4 N uptake by potato plants, under four N management practices, simulated by the model.

CONCLUSIONS

CSPotato model is a crop-growth simulation model for potato. The utility of this model was enhanced by linking it with CropSyst, which enabled the prediction of fate and transport of N under the potato-production system. The model predictions of crop yield and N uptake compared reasonably well with the respective measured parameters for Ranger Russet potato variety in the Pacific Northwest production conditions.

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